

# Grain Sedimentation in a Giant Gaseous Protoplanet

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## Abstract

We present a calculation of the sedimentation of grains in a giant gaseous protoplanet such as that resulting from a disk instability of the type envisioned by Boss (1998). Boss (1998) has suggested that such protoplanets would form cores through the settling of small grains. We have tested this suggestion by following the sedimentation of small silicate grains as the protoplanet contracts and evolves. We find that during the course of the initial contraction of the protoplanet, which lasts some  $4 \times 10^5$  years, even very small ( $> 1\mu\text{m}$ ) silicate grains can sediment to create a core both for convective and non-convective envelopes, although the sedimentation time is substantially longer if the envelope is convective, and grains are allowed to be carried back up into the envelope by convection. Grains composed of organic material will mostly be evaporated before they get to the core region, while water ice grains will be completely evaporated. These results suggest that if giant planets are formed via the gravitational instability mechanism, a small heavy element core can be formed due to sedimentation of grains, but it will be composed almost entirely of refractory material. Including planetesimal capture, we find core masses between 1 and  $10 M_{\oplus}$ , and a total high-Z enhancement of  $\sim 40 M_{\oplus}$ . The refractories in the envelope will be mostly water vapor and organic residuals.

## 1 Introduction

The mechanism of giant planet formation is still a matter of debate. The two main candidates are core accretion (see, e.g. Pollack et al. 1996) and disk instability (see, e.g. Boss 1997). In the core accretion scenario, kilometer-sized planetesimals collide and accrete to form a core. As this core grows, it begins to attract the surrounding gas. By the time the core has reached a mass of some  $10 M_{\oplus}$ , the accretion rate of the gas becomes very high and a Jupiter-mass object is formed (Pollack et al. 1996, Hubickyi et al. 2005).

The alternative scenario invokes a local gravitational instability in the gas disk surrounding a young star. Such an instability can lead to the creation of gas clumps which evolve to become giant planets. Such a mechanism of planet formation would seem to imply that the resultant planet has a solar ratio of elements. Observations of Jupiter indicate that the planet's envelope is enriched in heavy elements by a factor of  $\sim 3$  over the solar ratio to hydrogen (Young 2003). In addition, recent models of Jupiter's interior that fit the gravitational moments (Saumon and Guillot, 2004) indicate that Jupiter's core is between 0–6  $M_{\oplus}$ , smaller than earlier estimations. However, the overall enhancement of heavy elements in the planet, according to these models, is of the order of 20 – 40  $M_{\oplus}$ , or 3 – 6 times the solar value.

The core instability model requires a core of the order of  $\sim 10M_{\oplus}$  to reach the rapid gas accretion stage, while the disk instability can, in principle, form a giant planet with no core at all. Indeed a simple interpretation of this scenario would seem to require this. Therefore, if Jupiter does turn out to have a substantial core, the disk instability model must provide a mechanism for forming one. Boss (1997, 1998) has suggested that a solid core can be formed by sedimentation of dust grains to the center of the protoplanet before the protoplanet contracts to planetary densities and temperatures. In this paper we investigate this possibility by applying the microphysics of grain coagulation and sedimentation to silicate grains in a Jupiter-mass protoplanet with initial conditions similar to those in a newly formed clump.

## 2 Model

We start with an isolated spherical clump of one Jupiter mass with an initial radius of  $\sim 0.5$  AU. We take the clump to be isolated so that no external influences on the body (e.g. disk shear, solar irradiation, etc.) are included. In fact, solar radiation can strongly affect the internal temperature profile, and we discuss the consequences of this in the conclusion. For the isolated planet, our starting physical parameters fit the expected initial conditions of a newly-formed clump according to the disk instability model (see, e.g. Boss 1997), and follow its evolution using a stellar evolution code. This code, which was originally developed for stellar-mass objects, solves the standard equations of stellar evolution with an adaptive mass zoning which is designed to yield optimal resolution. The model uses the equation of state of Saumon et al. (1995) with an addition of our own equation of state computed for lower pressure regions, assuming that the gas is a solar mix of hydrogen and helium. We use opacity tables that include both gas and grain opacity based on the work of Pollack et al. (1989). Further details of the code can be found in Helled et al. (2006 - hereafter called paper I).

Under the given conditions, a quasistatic gas sphere will initially have a central temperature of 357 K and a photospheric temperature of 26 K. Fig. 1 shows the variation of the central temperature, central pressure, and some other planetary parameters as a function of time for the evolving protoplanet. This is for a solar composition model without a heavy element core. The consequences of adding a core will be discussed in

the conclusion. Such a clump contracts for a few times  $10^5$  years before it reaches a central temperature of  $\sim 2000$  K. At this point there is enough hydrogen dissociation near the center so that a dynamical collapse occurs. Until that time, the radius changes slowly and dust grains within the clump can coagulate and grow, and finally, settle to the center. In his original estimate for the grain sedimentation time in such a protoplanet, Boss (1998) assumed that the body was in radiative equilibrium. We find, however, that such a clump is fully convective, aside from a thin outer radiative zone. This is consistent with the earlier results of Bodenheimer et al. (1980) and Wuchterl et al. (2000). As a result, convection must be taken into account in simulating the settling of dust grains to the center of a protoplanet.

## 2.1 Planetesimal Capture

In addition to the grains originally present in the body, extra solid material will be accreted in the form of planetesimals. We computed the rate of planetesimal capture as in paper I. The trajectories of the planetesimals in the protoplanetary envelope, and the resulting ablation were computed using the procedure described in Podolak et al. 1987. By averaging over the different impact parameters we were able to compute the mass of material deposited in each atmospheric layer as a result of planetesimal ablation. This mass deposition is not only a function of time and depth in the protoplanetary atmosphere, but also depends on the size and composition of the planetesimal and its random velocity far from the protoplanet.

We assumed that the ablated material was deposited into the layer in the form of grains with the same initial radius as the grains originally present in the body. This is not unreasonable, since the planetesimals are themselves composed of those same grains. It is certainly possible, however, that processing inside the planetesimal will lead to a different size distribution. Furthermore, at least some the ablated material is released as vapor which then recondenses. The size distribution resulting from such a process will no longer be the same as the size distribution in the original material, so that future work will have to examine the effect of this assumption in more detail. Below, we present results for different choices of the initial grain size.

## 2.2 Grain Microphysics

We assume that the composition of the gas is solar ( $Z=0.02$ ) so that a  $1M_{Jupiter}$  sphere will contain  $3.8 \times 10^{28}$  g  $\sim 6M_{\oplus}$  of heavy elements. Of this approximately  $7.7 \times 10^{27}$  g is refractory material, while the rest are more volatile ices and organics. Since the temperatures in the body are fairly low, most of this high-Z material will initially be in the form of small grains. We assume these grains are spheres with an initial radius,  $a_0$ . At each radius  $r$  at some time,  $t$ , let the number density of grains of mass between  $m$  and  $m + dm$  be given by  $n(m, r, t)dm$ . The change in this number with time due to collisions is described by the Smoluchowski

equation (see, e.g. Wetherill 1990)

$$\begin{aligned} \frac{\partial n(m, r, t)}{\partial t} = & \frac{1}{2} \int_0^m \kappa(m', m - m') n(m', r, t) n(m - m', r, t) dm' \\ & - n(m, r, t) \int_0^\infty \kappa(m, m') n(m', r, t) dm' + q(m, r, t) - \nabla \cdot F \end{aligned} \quad (1)$$

where  $\kappa(m, m')$ , the *collision kernel*, is the probability that a grain of mass  $m$  will collide with and stick to a grain of mass  $m'$ . This includes collisions due to the Brownian motion of the grains as well as the fact that larger grains sediment faster than smaller grains and can overtake them. For the case of convection, where small grains may be carried with the convective eddy while large grains would not, the situation is more complex. Studies by Volk and collaborators (Volk et al. 1980; Markiewicz et al. 1991) have examined the behavior of the relative velocities between different sized grains for such a case. A useful fit to their numerical results is given by Weidenschilling (1986), and we have used that prescription.

The first integral on the right hand side equals the rate of formation of grains of mass  $m$  by collisions between a grain of mass  $m'$  and a grain of mass  $m - m'$ . The second integral is the rate of removal of grains of mass  $m$  when such a grain combines with a grain of any other mass.  $q$  is a source term which, in our case, can represent the addition of grains by the ablation of infalling planetesimals. The grain distribution can also be changed by sublimation of grains when the ambient temperature is high enough, and we allowed for this possibility in our calculations.

In principle, recondensation can also occur when the gas temperature is low enough, and the concentration of vapor in the gas phase is high enough. Since we did not follow the changes in vapor concentration in our calculations, we did not consider the possibility of recondensation. The temperature in any given region increases as the protoplanet contracts, so it is unlikely that recondensation will be an important effect.

The term involving  $F$  is the transport term. This can be either via gravitational settling through the gas or via turbulent transport if the gas is sufficiently convective. In the first case the flux of grains of mass  $m$  due to sedimentation is given by

$$F_{sed}(m, r, t) = n(m, r, t) v_{sed}(m, r, t) \quad (2)$$

where  $v_{sed}(m, r, t)$  is the sedimentation velocity of a grain of mass  $m$  at radius  $r$  and time  $t$ .  $v_{sed}$  is found from the force balance between the local gravitational force and the gas drag on the grain. In the case of convective transport, we use an eddy diffusion approximation where the flux is given by

$$F_{conv}(m, r, t) = -K(r, t) \left[ \frac{\partial n(m, r, t)}{\partial r} + \frac{n(m, r, t)}{H(r, t)} \right] \quad (3)$$

Here  $K(r, t)$  is the eddy diffusion coefficient, and is give by  $K = vL$  where  $v$  is the convective speed of the gas and  $L$  is some relevant length. In this study we took  $L$  to be the pressure scale height of the gas. The

convective speeds are estimated from the mixing length recipe. In the above equations we have included the time explicitly in order to emphasize that the background atmospheric parameters are changing with time as the protoplanet evolves.

We divided up the size distribution among a number of bins (typically between 10 and 40) that are logarithmically spaced in mass. We choose the number of bins according to the initial grain size, taking care to always allow growth to at least 10 cm. In practice the grains rarely grow larger than this. Initially the entire grain mass is in the smallest mass bin. Bins representing the larger sizes are populated only by grain growth through coagulation and coalescence. We assume that the grains are spherical and have a fractal dimension of three. The code we used to compute the microphysics is derived from the codes described in Podolak and Podolak (1980) and Podolak (2003), and further details can be found in those references.

## 2.3 Core Boundary Condition

There are two possibilities once a grain reaches the core region of the protoplanet. One possibility is that the grain attaches itself to the core, and loses its identity as a separate grain. In this case, it will not be mixed back up into the envelope, and we remove it from the calculation. We will refer to this as *case 1*. A second possibility is that the grain retains its identity, while in the core region, and can be mixed back up into the envelope by convection. This will be referred to as *case 2*. Below we present results for both scenarios.

# 3 Model Results

## 3.1 Silicate grains - without convection

In order to get a feeling for the behavior of the model, we first present some simplified cases. In the first, we have suppressed the convective transport. With no convection, the grains remain in the core once they reach it, since we have not included any mechanism for mixing them back up. In this instance there is no difference between cases 1 and 2. We assume silicate grains with a density of  $2.8 \text{ g cm}^{-3}$  and follow them as they settle and grow. In agreement with expected solar composition, we take the mass ratio of grains to gas to be  $4 \times 10^{-3}$ . Fig. 2 shows the mass of grains integrated from the surface of the protoplanet down to radius  $r$  for different times. Again, for simplicity, we consider only the grains that were originally present in the clump, and neglect any additional source. The initial grain distribution is shown by the heavy solid curve. For  $a_0 = 1 \text{ cm}$  (solid curves) the grain settling is extremely quick and a pronounced settling is already apparent after only 150 yrs. After 1400 yrs the grains have almost completely settled to the core. In this computation and those which follow, we computed the energy released by the grains assuming that they settle to a core with a radius of  $10^9 \text{ cm}$ . This is roughly the radius of a silicate core of a few Earth masses. This energy was included in computing the evolution of the protoplanet.

For  $a_0 = 10^{-2}$  cm (dotted curves) the grains settle more slowly in the outer layers, and for the first 500 years or so the mass of grains in the outer half of the protoplanetary radius remains constant. Nearer the core, however, they settle faster. This is because the higher number density of grains in that region make the growth time shorter there. The grains closer to the center grow quickly, and sediment faster than the grains in the outermost layers because the time between grain collisions is inversely proportional to their number density. Since the grain number density is initially proportional to the gas density, the growth time will initially be inversely proportional to the gas density squared. The gas density increases by orders of magnitude towards the center of the body, and the growth time decreases accordingly. In our models the growth time near the center of the protoplanet can, indeed, be orders of magnitude shorter than the corresponding value near the edge of the body.

For  $a_0 = 10^{-3}$  cm (dash-dot curves), the number density is even higher, but the particles are much smaller. The net result is that these smaller grains grow even more quickly in the inner parts of the protoplanet, although they grow and sediment somewhat more slowly in the uppermost regions of the body than grains with  $a_0 = 10^{-2}$  cm. Still smaller grains (not shown) settle at about the same rate as the grains with  $a_0 = 10^{-3}$  cm. In general, grains with  $a_0 \leq 10^{-2}$  cm grow quickly and sediment faster than grains with  $a_0 = 1$  cm. Of course, if the grains are large enough, they will settle even faster. This can be seen in fig. 3, where we have plotted the mass of grains in the central shell as a function of time.

Here we see that, for  $a_0 = 10$  cm, the central shell fills very quickly because of the short settling time of such large grains. For  $a_0 = 1$  cm, the core growth is much slower, as expected. The trend continues for grains with  $a_0 = 0.1$  cm, though to a slightly lesser extent, and reverses for smaller values of  $a_0$ . At  $a_0 = 10^{-2}$  cm, grain growth becomes efficient enough so that they can grow before they get a chance to settle, and the net result is a shorter core formation time.

### 3.2 Silicate grains - including convection

When convection is allowed, and the grains are required to remain in the core upon reaching it (case 1), the core forms very quickly. Downward eddies bring grains into the core, but the upward eddies return empty of grains. Thus there is a strong steady flux of grains into the center, and a core is formed in a few hundred years even for the smallest grains. If the grains are larger than  $\sim 10$  cm, their sedimentation speed is several tens of meters per second, even in the denser regions near the center, which is comparable to or greater than the convective speed of the gas eddies. Thus, once the grains reach this size they are no longer seriously affected by convective motions. They fall faster than those dragged by the convection, and the core is formed in a somewhat shorter time.

It is important to note that in our models the actual core is not resolved. At the relevant stage of evolution, the central shell in our models has a radius of  $10^{11}$  cm, while a core of several  $M_{\oplus}$  would have

a radius  $\sim 10^9$  cm. The grain number density in this central region is high enough, however, so that the grains quickly grow larger than 10 cm, and are not significantly influenced by convective motions. In this case it is easy to show that the time to sediment to a core with radius  $10^9$  cm is only a few years.

Fig. 4 shows the core formation for the case where convection is allowed to mix the grains back into the envelope (case 2). Again we do not allow for additional grains to be added via planetesimal accretion. For this case, the growth of the core is delayed by convective mixing until the grains can grow large enough ( $\sim 10$  cm) so that they are no longer easily mixed by the convective eddies. Thus grains with  $a_0 = 1$  cm (solid curves) require a few times  $10^4$  yrs to form a significant core. Much smaller grains behave in a very similar way. The curves for  $a_0 = 10^{-2}$  cm (dotted curves) fall almost exactly on the  $a_0 = 1$  cm curves, so that, for clarity, we show them for intermediate times. The two distributions follow nearly identical evolutionary paths. Grains with  $a_0 = 10$  cm (dashed curves), however, sediment significantly faster, since they are large enough not to be mixed by the convective eddies. Thus, for grains with  $a_0 \lesssim 1$  cm, for case 2, a core can be formed in  $\sim 7.8 \times 10^4$  yrs even when convective mixing is present.

For larger grains the core forms even more quickly. The time  $7.8 \times 10^4$  yrs is significant, because after this time the inner parts of the protoplanet reach temperatures of  $\gtrsim 1300K$ , and this is high enough to evaporate silicates. At this point core growth stops. If the material that reaches the central region can somehow be protected from vaporizing after this time, this core will survive. This might be the case if the silicates remained bound in the core. If this were the case, it would not matter much what the actual phase of the material is, since it would be segregated from the lighter hydrogen and helium. A proper study of the fate of the material in the center during and after the rapid contraction phase would require an equation of state that includes high-Z material. Work to that end is in progress. We thank an anonymous referee for pointing out that any silicate grains reaching the core region after this point may form a silicate-rich layer surrounding the core. We point out that this might mimic a larger core when the gravitational moments of the body are computed.

## 4 Sedimentation Including Planetesimal Capture

In paper I we showed that a significant amount of solid material can be added to the protoplanet via planetesimal capture. The total mass of available material depends on the disk properties, while the capture rate depends on the planetesimal characteristics. This additional solid material resulting from planetesimal accretion will act as a source of grains in the protoplanetary envelope. As noted above, the size distribution of this additional material may be different from that of the initial grain distribution in the envelope, but for the sake of simplicity we have assumed that both the original grains and the ones added via planetesimal accretion have the same  $a_0$ . The grains were added to the envelope at a rate consistent with the planetesimal capture rate computed in paper I. The radial distribution of the deposition was determined by following planetesimal

trajectories through the envelope and averaging over the planetesimal impact parameters. The grain source was then taken to be the average mass deposited in a layer of the envelope by ablation multiplied by 0.23 in order to include only the refractory component.

We considered three different sizes of planetesimals: 1, 10, and 100 km and assumed that these planetesimals were composed of a mixture of rock, organic material (CHON), and ice. The surface density of solid material was taken to be  $10\text{g/cm}^3$  and the random velocity of the planetesimals was taken to be  $10^5\text{ cm s}^{-1}$  (Pollack et. al 1996). The protoplanet can capture 1 km planetesimals almost immediately, but must contract to somewhat higher densities before it can capture 10 km planetesimals. In this case, the additional source of grains becomes active only after  $4 \times 10^3$  yrs. 100 km bodies can be captured only after  $3.5 \times 10^4$  yrs. After about  $7.8 \times 10^4$  yrs the temperatures near the center become too high and the silicate grains evaporate. Thus, if the planetesimals are 100 km or larger, they will contribute much less to the core mass.

It is important to note that we have neglected the gravitational energy released as the grains sediment. This will produce a higher luminosity than we have computed, and will lengthen the contraction time. We have also neglected the effect of the core in computing the structure of the protoplanet. The core will cause an increased compression in the deep interior which should shorten the contraction time. While these two effects act in opposite directions, they are difficult to quantify without a more careful calculation. We are currently investigating these effects in more detail.

Table 1 shows the time it takes the grains to sediment to a core, and the final core mass for the case of no convection. These core masses are to be compared to the  $7.7 \times 10^{27} (\sim 1.3M_{\oplus})$  g that are available from the initial refractory grain distribution. Even the 100 km planetesimals give a core that is twice as massive. Table 2 shows the same results when convection is included (case 2). The core masses are about half those of the non-convective case. Here, because the protoplanet must contract significantly before the 100 km planetesimals can be captured, and the grains must grow sufficiently to overcome convective mixing, many of the grains evaporate before reaching the core, so that planetesimal capture does not enhance the core mass if the planetesimals are as large as 100 km.

## 5 CHON and Ice Grains

The above calculations were done assuming that the grains are composed of silicates, and only the fraction of the high-Z material that is in silicates was considered. In fact, the high-Z mass will be divided almost equally among rocky material, organic material (CHON), and water ice. The latter two materials are much more volatile and will evaporate earlier in the course of the protoplanet evolution. To see the effect on our models, we reran the calculations using these materials. The composition of CHON is not known and we considered two possibilities. The first was the organic material proposed by Obrec (2004) as comprising the grains in the coma of comet Halley. These have an average density of  $1.44\text{ g cm}^{-3}$ , and a vapor pressure



given by

$$P_{vap} = 5.53 \times 10^7 e^{-L/RT}$$

where  $L = 80 \text{ kJ mole}^{-1}$ ,  $R$  is the gas constant and  $T$  is the temperature.

A second material we considered was hexacosane ( $\text{C}_{26}\text{H}_{54}$ ) which is a paraffin-like substance with average density of  $2 \text{ g cm}^{-3}$ . Its vapor pressure is given by

$$P_{vap} = 6.46 \times 10^{13} e^{-12484.5/T}$$

In both cases, the grains dissolve in the envelope before they reach the core region for  $a_0 \leq 10 \text{ cm}$ . It is only when  $a_0 > 10 \text{ cm}$  that the grains can sediment quickly enough to avoid being evaporated before they reach the core region. Again, we assume that once the grains are incorporated into the core, they are somehow "immune" to further evaporation. Thus CHON would not contribute to core formation unless the grains were larger than about  $10 \text{ cm}$ . Water ice grains evaporate at even lower temperatures, and have no chance of contributing to the material in the core. This leads to the interesting conclusion that a planet formed by the disk instability model can have a sizable core, but that core would have to be composed almost entirely of refractory material.

## 6 Conclusion

We present a calculation of grain sedimentation inside a protoplanet formed via the disk instability scenario. During the first  $\sim 10^5 \text{ yr}$  the clump is cold enough to let silicate grains settle to the center and create a heavy element core. This is true for all grain sizes we considered ( $a_0 \geq 10^{-4} \text{ cm}$ ). Grains smaller than this will have high enough number densities so that they will grow quickly into the size range we considered. Core formation proceeds whether the envelope is convective or not, although the convective envelope delays core formation substantially for smaller grains. In all cases a core can be formed before the temperatures near the center get high enough to evaporate the silicate grains. If the silicate material that reaches the central region and is incorporated into a core is immune to further dissolution, core masses of some  $4 \text{ M}_{\oplus}$  can be obtained. This includes material added to the planet later via planetesimal capture. If the planetesimals are of the order of  $100 \text{ km}$  radius or larger, they will not be captured until the protoplanet contracts sufficiently. This delay means that the envelope temperatures are higher when this additional mass settles, and not all the grains can reach the core before they are vaporized. For such large planetesimals, we find that the core mass will be only  $\sim 1.7 \text{ M}_{\oplus}$ .

Grains consisting of ice or more volatile material cannot sediment quickly enough to avoid being vaporized before they reach the core region. Grains consisting of CHON depend on the volatility chosen. For hexacosane the grains evaporate before reaching the core at all the sizes we considered. For CHON that has the volatility suggested by Obrec (2004), only very large grains ( $\gtrsim 10 \text{ cm}$ ) can reach the core, and these add at most a

few tenths of an Earth mass to the total core mass. The remainder of this high-Z material would remain in the envelope, giving a high-Z mass in the envelope of some  $30 M_{\oplus}$ . Our simulations thus produce both core and envelope high-Z masses that agree very well with the values determined by fitting the gravitational moments of Jupiter (Guillot 1999, Saumon and Guillot 2004).

In this work, two very important effects have been neglected. The first is radiative heating by the surrounding medium. As Kovetz et al. (1988) have shown, such radiation tends to be deposited at a point where the optical depth is approximately equal to the ratio of the incoming flux to the outgoing flux. In our case, the isolated planet initially has a photospheric temperature of  $\sim 25$  K. If we take the protoplanet to be at 5 AU, the intervening gas and dust will have a high optical depth in the visible [e.g. Chiang and Goldreich (1997)], and the radiation falling onto the protoplanet will be mostly at the ambient temperature of the surrounding gas. This is model-dependent, but is of the order of 100 K (Lecar et al. 2006) so that the ratio of incoming to outgoing flux can be quite large. This will cause higher temperatures in the interior, and will make it more difficult for grains to survive long enough to sediment to the core. On the other hand, in the early stages the planet will stay extended longer, and this will allow more time for the grains to settle.

A second effect is the contraction of the gas near the center by the increased pressure due to the core itself. This too will heat the gas near the core, and will inhibit the grains from settling. This second effect seems more serious, since, in this scenario, the formation of the core itself inhibits further core growth. A proper treatment of this effect requires an equation of state for the core material, and work on this is in progress.

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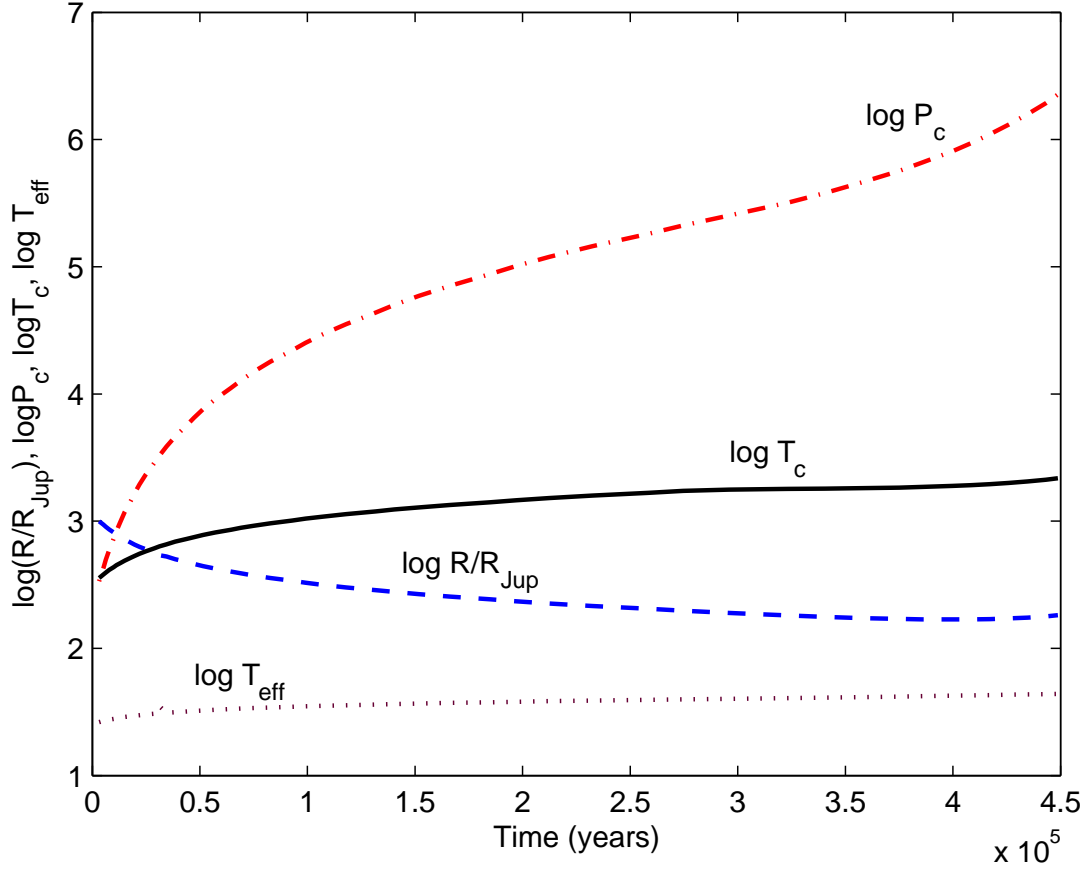


Figure 1: Central pressure, central temperature, radius, and effective temperature as a function of time. The effects of grain sedimentation and core growth are not included (see text).

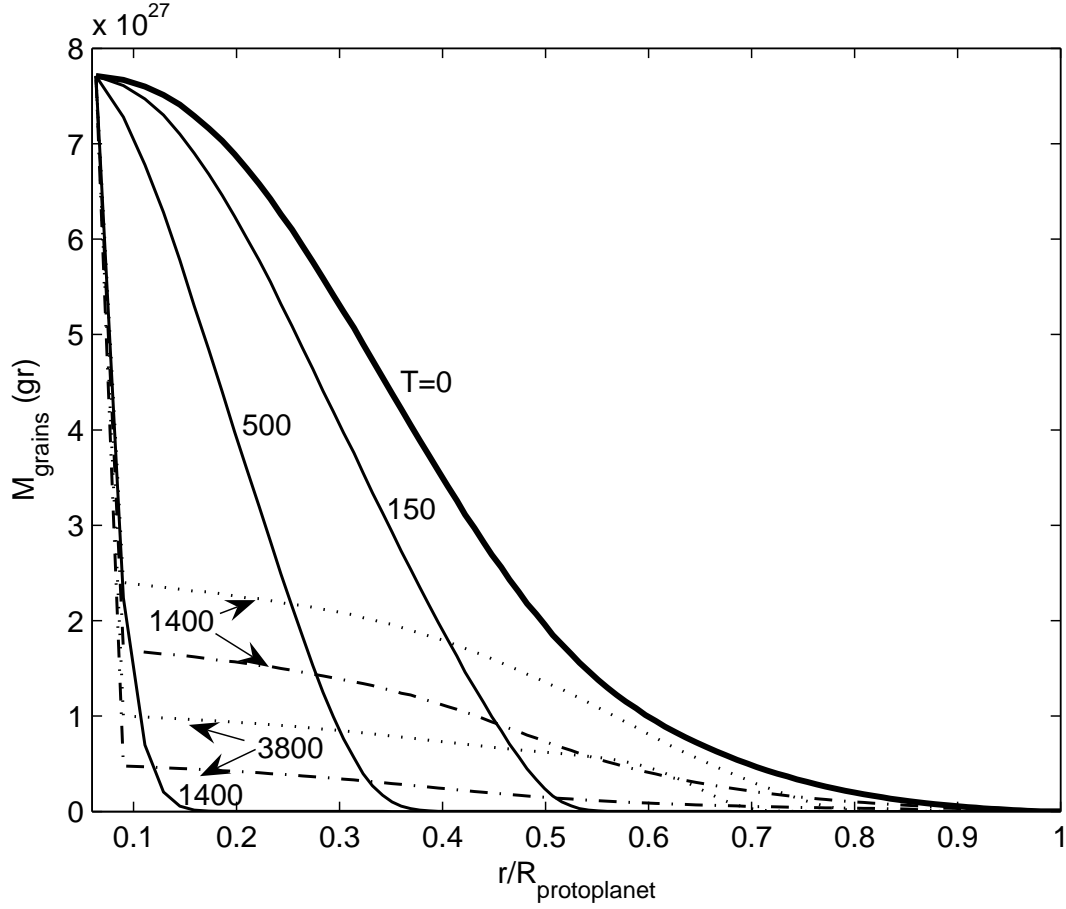


Figure 2: Cumulative mass of silicate grains integrated from the outer edge of the protoplanet inward as a function of normalized radius for various times (in yrs.) for grains with  $a_0 = 10^{-3}$  cm (dash-dot curves),  $10^{-2}$  cm (dotted curves), and 1 cm (solid curves). The initial grain distribution is shown by the heavy solid curve. There are no additional sources and convective transport is suppressed.

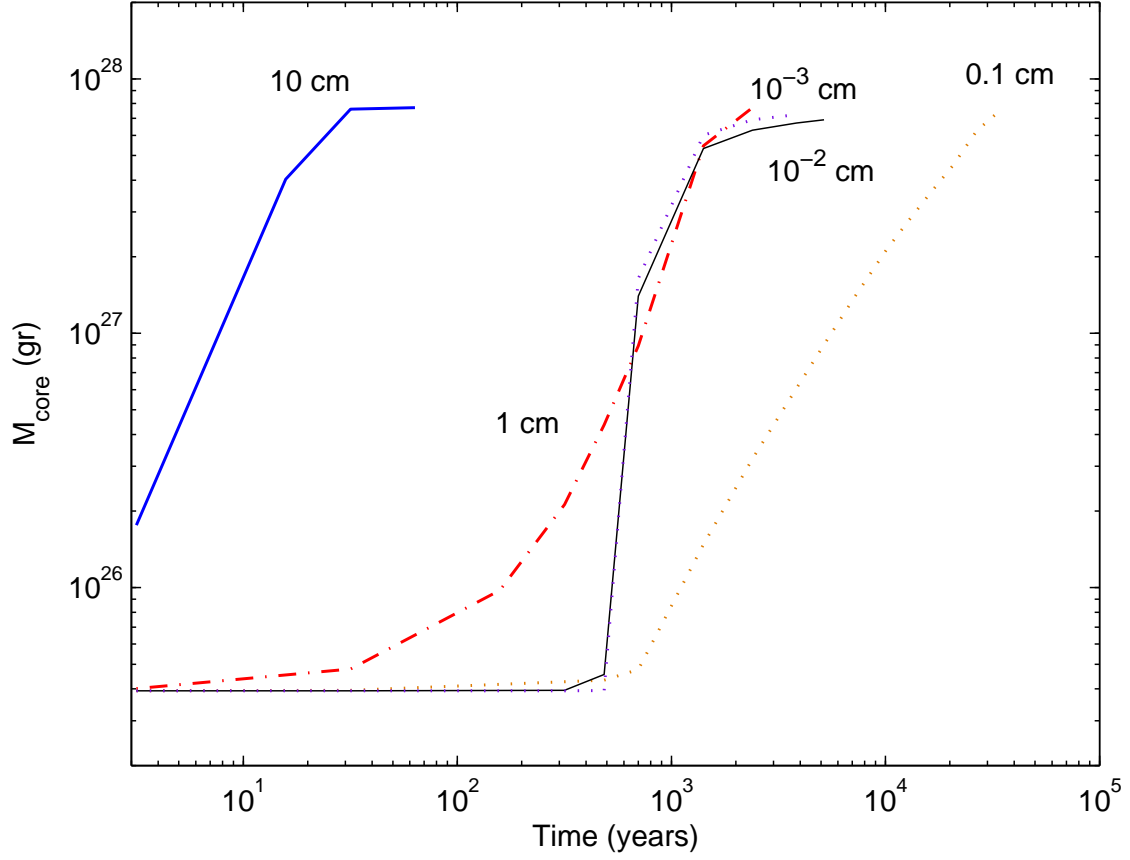


Figure 3: Core mass as a function of time for different values of  $a_0$ . The assumptions are the same as in Figure 2.

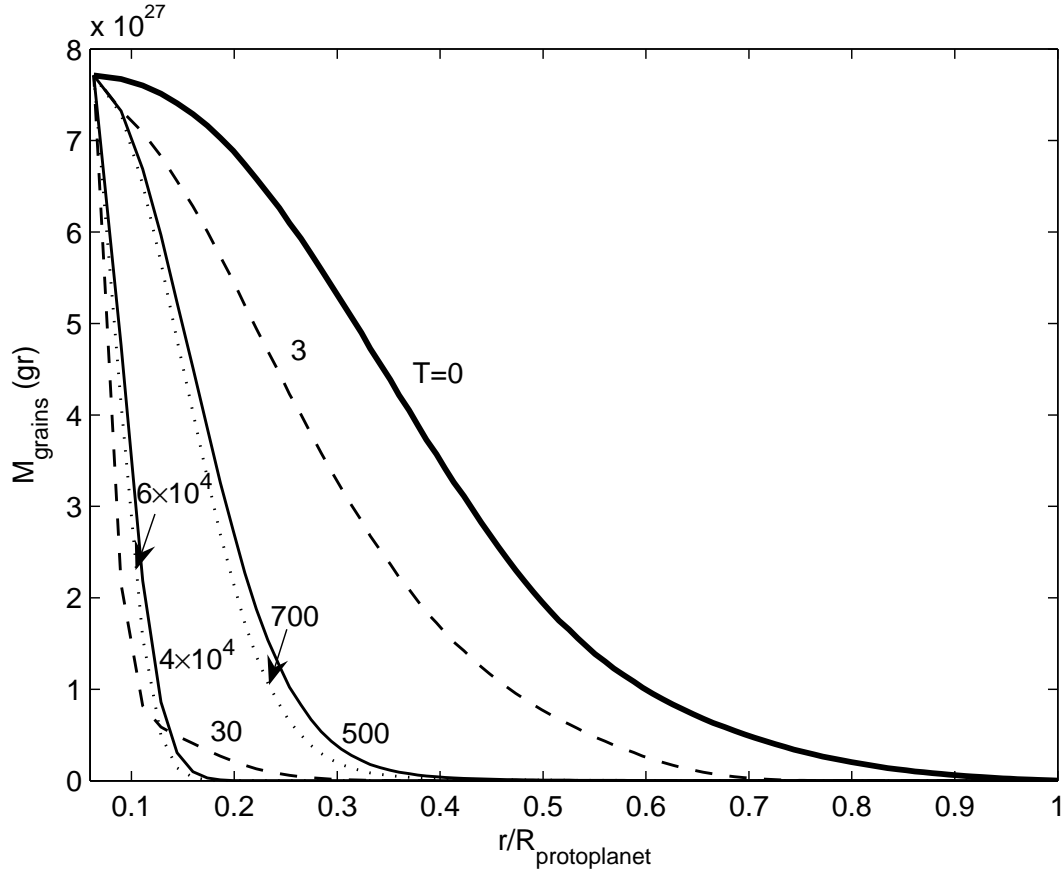


Figure 4: Cumulative grain mass as a function of time for grains with  $a_0 = 10$  cm (dashed curves),  $a_0 = 1$  cm (solid curves) and  $a_0 = 0.01$  cm (dotted curves) for convection for case 2. There is no additional grain source from accreting planetesimals.

	$r_{grain} = 1 \text{ cm}$		$r_{grain} = 0.1 \text{ cm}$		$r_{grain} = 0.01 \text{ cm}$	
$r_p \text{ (km)}$	Time (yrs)	$M_{core}(M_{\oplus})$	Time (yrs)	$M_{core}(M_{\oplus})$	Time (yrs)	$M_{core}(M_{\oplus})$
1	$10^4$	9.44	$3.5 \times 10^4$	9.44	$10^4$	9.44
10	$4.5 \times 10^4$	9.26	$4.5 \times 10^4$	9.31	$4.5 \times 10^4$	9.32
100	$7.8 \times 10^4$	3.22	$7.8 \times 10^4$	3.16	$7.8 \times 10^4$	3.13

Table 1: The capture time and accreted mass for different cases in the absence of convection. All cases correspond to ice+rock planetesimals

	$r_{grain} = 1 \text{ cm}$		$r_{grain} = 0.1 \text{ cm}$		$r_{grain} = 0.01 \text{ cm}$	
$r_p \text{ (km)}$	Time (yrs)	$M_{core}(M_{\oplus})$	Time (yrs)	$M_{core}(M_{\oplus})$	Time (yrs)	$M_{core}(M_{\oplus})$
1	$7.8 \times 10^4$	4.47	$7.8 \times 10^4$	4.45	$7.8 \times 10^4$	4.47
10	$7.8 \times 10^4$	4.43	$7.8 \times 10^4$	4.41	$7.8 \times 10^4$	4.41
100	$7.8 \times 10^4$	1.68	$7.8 \times 10^4$	1.70	$7.8 \times 10^4$	1.71

Table 2: The capture time and accreted mass for different cases, with convection included. All cases correspond to ice+rock planetesimals